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**UAT MOPS**

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**Investigation of  
Possible Enhancements to the Universal Access Transceiver (UAT)**

**Prepared by James Higbie**

**The Johns Hopkins University/Applied Physics Laboratory**

**SUMMARY**

This note summarizes the results of investigations into several possible modifications to the UAT system enhancements designed to increase performance against burst interference caused by Link 16 (JTIDS/MIDS) transmitters. These changes are discussed in the context of improved UAT error detection and correction schemes proposed by MITRE in their working paper UAT-WP-2-03 ("Preliminary Results on Possible Enhancements to the Universal Access Transceiver (UAT)," by Warren J. Wilson and Myron Leiter).

## 1. Introduction

In UAT-WP-2-03, “Preliminary Results on Possible Enhancements to the Universal Access Transceiver (UAT),” MITRE proposes modifying UAT Reed-Solomon (RS) and Cyclic Redundancy Check (CRC) codec protocols as follows:

- Change the coding of the ground message to 6xRS(85,65), and add an 85x6 byte interleaver. Remove all six bytes of CRC.
- Change the coding of the long Automatic Dependent Surveillance-Broadcast (ADS-B) message to RS(46,34), and reduce the CRC to 2 bytes.
- Change the coding of the short ADS-B message to RS(26,18), and reduce the CRC to 2 bytes.

The above changes can be expected to significantly increase the ability of UAT transceivers to operate in the presence of Link16 interference, and they appear to be among the simplest and most direct way to do so. There are, however, many possible alternate or additional measures which could help. To more fully characterize the range of possible system modifications, and to help identify ways to further increase UAT performance should the MITRE-proposed changes prove insufficient, several investigations into other UAT modifications and related areas were undertaken at the Johns Hopkins University/Applied Physics Laboratory (JHU/APL).

The JHU/APL investigations were in seven general areas:

- Alternate Reed-Solomon (RS) coding parameters (symbol size and number of parity symbols) for the ground message.
- Erasure-based decoding for the ground message.
- Synchronizing UAT ground message slot times with Link 16 slot times.
- Synchronizing UAT ADS-B message transmissions with Link 16 slot times.
- Accuracy of using results for Link 16 interference alone with previous results (for interference from other UAT transmissions alone) to make predictions for combined interference environments.
- Impact on UAT ADS-B message reception of denser Link 16 interference environments consistent with Department of Defense (DoD) constraints on operations.
- Frequency-diversity (dual-channel) UAT operation.

## 2. Summary of Observations

Based on the calculations made, the conclusions reached may be summarized as follows:

- The proposed 8-bit RS symbol size is superior to designs with fewer numbers of bits per RS symbol. Designs with fewer than 6 blocks, however, should have performance

superior to that of the proposed design. If UAT modifications less expensive than replacing the RS chip do not provide adequate ground message performance, the possibility of decreasing the number of blocks per message may be worth investigating.

- Erasure-based decoding of the ground message can achieve significant further performance increase against Link 16 interference, should it be necessary. Implementing such an approach, however, may add significantly more expense than the MITRE-proposed coding changes.
- Worst-case coding performance of UAT ground transmissions could be significantly improved if their time slots were expanded from their current duration of 5.5 msec to something close to the Link 16 value (~7.5 msec for GPS-synchronized Link 16 networks, ~8.5 msec otherwise). Such schemes would reduce the number of slots available for ground messages to 21 to 24, however, but could achieve substantial increases (~30%) in overall throughput (number of slots times payload per slot).
- Performance can likely be improved if UAT units monitor Link 16 interference severity and adjust their ADS-B transmission times accordingly. It is difficult to quantify achievable improvement without a full network simulation of both Link 16 and UAT networks. The cost of implementing such a scheme appears low, but it would require UAT software and perhaps hardware modifications.
- Combining Link 16 interference results that don't include UAT interference with previous UAT network simulation results (which don't include Link 16 interference) can overestimate the Probability of Correct Message (PCM) by at least a few per cent, even for the assumed conditions of independent Link 16 and UAT interference. Since Link 16 and UAT interference can be dependent (owing to nulls in the UAT receive antenna pattern), larger errors can occur. Thus, while calculations using Link 16 interference by itself (as opposed to a full UAT plus Link 16 network simulation) can be used to rate the relative Link 16 tolerance of different mitigation approaches, such calculations should be used conservatively, allowing a margin for error of at least several percent in PCM, when estimating whether any given approach can achieve acceptable performance under combined conditions.
- Stacked-net Link 16 operation operating at combined effective Time Slot Duty Factors (TSDFs) of 400% or more can degrade UAT performance unacceptably, even with the MITRE-proposed enhancements, depending on the distances to the various Link 16 transmitters. Worst-case operational Link 16 environments may degrade the PCM achievable by UAT with the MITRE-proposed enhancements by 10% to 15% at ranges of about 100 nm. The lower number corresponds to Link 16 environments expected under current DoD constraints, while the larger number occurs under the assumed "DoD proposed" rules. Adding the effects of DME interferences and the slightly higher-than-product PCM combining discussed above, it appears that some additional UAT performance enhancements may be appropriate.

- Dual-channel frequency diversity operation, if spectrum were available, could greatly increase UAT capability to operate in the presence of Link 16 interference.

These observations are offered to WG5 of SC-186 for its consideration. More detailed discussion of the investigations which led to them are provided in the following section.

### 3. Detailed Discussion

#### 3.1 Alternate RS Code Parameters for the Ground Message

The symbols used for RS coding in the current and MITRE-proposed UAT designs are 8-bits long. Link 16 transmitters are on the air for bursts lasting about 6.5 usec (about 7 UAT bits). Assuming strong interference, bit errors occur at a rate of 50% and the average number of bits included from the first bit error to the last during a Link 16 burst is about 5. Depending on its alignment relative to the RS symbol boundaries, such an error burst may cause either one or two 8-bit RS symbols to be wrong. For a 5-bit error burst, the average number of 8-bit RS symbol errors will be  $(8+5)/8$ .

Each of the ground message blocks in the proposed RS(85,65) design can tolerate 10 symbol errors or  $10 \times 8 / (8+5) = 6.15$  Link 16 bursts. The entire 6-block message can therefore tolerate 6 times this number or about 37 Link 16 bursts.

An alternate design was considered using 6-bit RS symbols, specifically 11 blocks of RS(62,48). (The number of blocks increases because 6-bit symbols cannot be used with RS blocks having more than 63 symbols.) This design provides very nearly the same message size and transmission time as the proposed 6-block 8-bit RS(85,65) (message size is ~ 1.5% longer and transmission time is ~ 0.3% longer). With 6-bit symbols, the average number of symbol errors per Link 16 burst increases to  $(6+5)/6$ , and each block can now only tolerate 7 symbol errors or  $7 \times 6 / (6+5) = 3.82$  Link 16 bursts. The entire 11-block message, however, can tolerate 11 times this number or 42 Link 16 bursts.

Because the 6-bit symbol design can tolerate 42 Link 16 bursts per message, or about 14% more than the proposed 8-bit design, it might be concluded its performance will be better. This conclusion would only be true, however, if symbol errors were distributed equally among all RS blocks. This is not the case, and the average number of symbol errors per block is smaller than the largest number of symbol errors in any block. It is this largest number of symbol errors per block which must be within the RS decoding capacity for the entire message to be correct. The more blocks there are in the message, the bigger the difference between the largest and average numbers of errors per block, so the apparent advantage of the 6-bit symbol design is counterbalanced by the increased number of blocks it requires.

To determine which of these contrary effects was more important, a simulation was run under the following simplifying assumptions:

- Link 16 transmissions occur with a fixed probability, independent of past history, every 13 bits and last 6.5 bits.
- These 13-bit hop times are random relative to the start of the UAT ground message.
- When Link 16 bursts occur, bit error rate (BER) = 50%, otherwise BER = 0.

The Link 16 burst probability per hop was varied and curves of PCM vs. Link 16 Burst Probability were computed for both coding designs (see Appendix, slides 1-3). For this simulation, an interleaved transmission design was assumed, as proposed.

It was found that at 50% PCM both designs could tolerate the same Link 16 burst probability (about 9%), but at 90% PCM the 8-bit design outperformed the 6-bit design somewhat. The conclusion of this investigation was therefore that the proposed 8-bit RS symbol size is superior to designs with fewer numbers of bits per RS symbol.

The penalty for increased number of blocks suggests another alternative for RS coding parameters: Maintain the 8-bit symbols but use fewer than 6 blocks. To maintain code rate, such a design requires more than the 20 parity symbols per block supported by the RS codec chip used in the current UAT hardware. One way to accomplish this would be to use an RS codec available in Field-Programmable Gate Array (FPGA) core libraries from the FPGA manufacturer Xilinx. This function would then be included by upgrading the Xilinx FPGA already used in the current UAT hardware to perform other custom high-speed digital processing.

FPGA designs are available to decode blocks with at least 32 parity symbols, so a candidate ground uplink message design with about the same total payload and FEC lengths as the proposed 6-block RS(85,65) would be 4 interleaved blocks of RS(128,98). (The extra 16 bits of total length could be taken from the 24-bit pad which was originally used to permit the synch detection circuitry time to initialize, but which is not expected to be required once re-triggerability is included in the hardware design.)

### **3.2 Erasure-Based Decoding For The Ground Message**

If the UAT decoder could monitor the signal strength on every bit, burst interference at levels well above that of the desired signal could be identified, and bits received during these times could be disregarded. This “erasure decoding” technique can increase performance substantially since an RS block can tolerate twice as many erasures as errored symbols. On the other hand, error detection performance decreases when erasures are present so that the Probability of Undetected Message Errors (PUME) increases. As a result, erasure decoding would require restoring CRC protection to achieve an adequate PUME. For the ground message, this can be accomplished with small enough overhead (~0.6% for a 24-bit CRC) to be worth considering.

The current UAT RS codec chip supports erasure decoding, but making the necessary measurements to determine when strong burst interference is being received, and getting those measurements to the codec, requires additional hardware expense. There is

currently no hardware available to measure signal strength, which would appear to be the best way to detect the presence of an interference burst. Because the FM demodulator output is over-sampled at 6 times the bit rate and provides greater than 1-bit precision, however, data are already currently available which could be expected to provide some indication of a Link 16 interference burst, although how reliably this could be done is currently unclear. Additional hardware expense would still be required to convert this information into a burst detection signal and to provide the signal to the codec.

In any case, it can be expected that detection of interference bursts would be imperfect. , A simulation was run to determine the impact of imperfect burst detection on erasure-based decoding performance. A simplified approach like that used for the 6-bit symbol investigation was used here, except that the RS decoding process was no longer modeled fully. Instead, erased symbols and errored symbols were tallied for each block and if the number of erased symbols plus twice the number of non-erased but errored symbols exceeded 20 (based on RS(85,65) blocks), the block was counted as wrong. (Another minor change was that Link 16 bursts were assumed synchronized with UAT bits and lasted 7 bits.)

It was assumed that the Link 16 burst detector would make errors in the estimated burst start and stop times, and these errors were modeled as being normally distributed. If the start time was estimated to occur later than the stop time, the burst was not detected. The mean start time error was assumed to be the negative of the mean stop time error, so that on average the center of bursts was estimated without bias, but the average length of the burst could be set to be estimated as either longer or shorter than actual. The errors in estimated start and stop time for each burst were assumed to be independent and independent of errors on any other bursts. The burst detection errors were therefore characterized by two parameters, the burst length bias and the standard deviation (rms variability about the mean bias for start or stop times).

Performance curves were computed as before, of PCM vs. Link 16 Burst Probability. Such curves were computed with and without erasure-based decoding. For the erasure-based case, curves were computed for a range of error bias and standard deviation values for the interference burst detector. Performance for each case was characterized by the Link 16 Burst Probability for which a 90% PCM was achievable (see Appendix, slides 4-7).

Based on the simulations, it was found that when burst times could be accurately estimated, erasure-based decoding of the proposed 6-block interleaved RS(85,65) achieved the expected 2-times increase in Burst Probability that could be tolerated. This is a substantial increase: For example, the performance increase from the current 2-block RS(255,235) to 6-block non-interleaved RS(85,65) corresponds to about a 2.5-times increase in allowed Burst Probability, and the increase achieved by interleaving 6-block RS(85,65) corresponds to about a 1.4-times increase.

It was further found that performance was relatively unaffected by burst time errors with a standard deviation of 1 bit or less, and that for larger standard deviations degradation

was graceful. For example, when the burst time errors reached a standard deviation of 2 bits (a fairly large error for both ends of a 7-bit burst), the performance dropped from 2-times increase in allowed Burst Probability to about a 1.5 times increase.

(These results assume that the burst detector is designed to have close to zero bias. It was found that when burst detector errors were rare a bias of about 1 bit too long was best, but when they were frequent, a bias in the direction of underestimating burst length was best. For example, at a burst time error standard deviation of 2 bits, a bias of about 1 bit too short was best.)

The conclusion of this investigation was therefore that erasure-based decoding of the ground message can achieve significant further performance increase against Link 16 interference, should it be necessary. Implementing such an approach, however, may add significantly more expense than the MITRE-proposed coding changes. (In addition to the receiver hardware costs discussed earlier, receiver retesting for network performance modeling can also be expected to be more expensive.)

### **3.3 Synchronizing UAT Ground Messages With Link 16 Slot Times**

It was noted in the MITRE working paper that both Link 16 slot times and UAT ground message time slots are synchronized, so that Link 16 transmissions will interfere with some ground message slots much more severely than others. MITRE suggested that some sort of slot time randomization for each ground message transmitter could improve things. An alternate approach, discussed here, is to synchronize them more closely.

Link 16 hops within which interference bursts can occur do not repeat continuously, but are themselves concentrated in intervals of either 3.354 msec (for the 258-hop Link 16 message) or 5.772 msec (for the 444-hop message) within every 7.8125-msec Link 16 time slot. Since there are exactly 128 of these slots every second, Link 16 slot boundaries occur in fixed relationship to each of the current UAT ground message time slots. The timing within the 7.8125-msec slot when a given Link 16 transmitter may interfere with a given UAT receiver depends on the ranges involved, but each Link 16 transmitter will be off the air continuously for 57% of each 7.8125-msec slot for 258-hop messages, of for 26% of each slot for 444-hop messages (see Appendix, slides 8-9).

Currently, Link 16 slot times are not required to be synchronized to Universal Time, so the portions of the Link 16 slot when transmissions are less likely are not known to the UAT. In the future, however, Link 16 networks may be synchronized using Global Positioning System (GPS) receivers, so that every network will tend to be off the air at the same times within each slot. Optimum UAT system operation in the presence of strong Link 16 interference will depend on whether or not the Link 16 and UAT systems operate synchronously or asynchronously, so these two different cases need to be considered separately.

In the special case that Link 16 and UAT are both GPS synchronized, UAT ground transmitters could take advantage of the Link 16 off-times if the UAT ground time slots were expanded from their current duration of ~5.5 msec to something close to the Link 16 value of 7.8125 msec, say ~7.5 msec. Coding could then be designed to maximize throughput during the times when Link 16 transmissions are most likely to be off the air, and to maximize interference suppression or be off the air during times when Link 16 transmissions are most likely to be on the air. Message error performance could then be substantially improved and would be much more uniform from UAT slot to slot. The longer message time would allow significant improvement in interference resistance and increased message data for each of the longer slots. Note that with longer UAT time slots, the number of time slots must decrease to 23 or 24 to provide the same amount of time for the air-to-air portion of UAT transmissions.

In the general case when Link 16 is not GPS-synchronized, the on-the-air time for UAT ground transmissions could be increased from its current value of ~ 4.1 msec to something close to the Link 16 slot time, say 7.5 msec. With a ~1-msec guard band between slots (compared to the current ~ 1.5 msec guard band), each UAT ground slot would then be ~8.5 msec long, and there would only be time for about 21 of them. In this case, portions of the UAT time slot when Link 16 transmissions are most likely are not known, so the coding would remain at a fixed rate throughout the slot.

One possible transmission design for this asynchronous case, assuming the 32-parity-symbol decoder discussed in Section 3.1 were available, would be to send a 36-bit synch preamble followed by 2560 bits of payload-plus-FEC followed immediately by two more such 2596-bit sequences. The three synch preambles would mean that the UAT bit clock would have to coast only slightly longer before resetting than in the current design (2.46 msec instead of 1.96 msec). (If this coast time is too long, four synch preambles could be used.) The 7680 total bits of payload-plus-FEC could be 6 interleaved blocks of RS(160,128) in order to achieve a comparable code rate (0.8) to MITRE's proposed RS(85,65) design (rate = 0.765). With 128 payload bytes per block, the total payload carried by all slots would be about 29% higher than the 32-slot RS(85,65) enhanced design proposed by MITRE.

Among the costs to such a scheme is decreased flexibility to configure ground uplink broadcasts with a smaller number of total slots. The magnitude of this effect has not yet been investigated.

### **3.4 Synchronizing UAT ADS-B Messages With Link 16 Slot Times**

Link 16 transmissions are more much more likely to be on the air halfway through each Link 16 slot than at the start or end of the slot. Heavy Link16 interference will therefore degrade UAT ADS-B messages sent with MSOs near the middle of Link 16 slots more severely than messages sent with MSOs near the Link 16 slot boundaries. Since the Link16 slot timing repeats every second, like the MSOs, the same MSOs are affected every second.



In the case of GPS-synchronized Link 16 transmissions, it would therefore be possible for a UAT unit to estimate the level of Link 16 interference by monitoring message ADS-B receptions and determining whether as many receptions are occurring during the middle half of Link 16 slots (“bad” MSOs, about 16 per Link 16 slot) as during the first and last quarter of the slots (“good” MSOs). A significantly larger number of ADS-B messages received during good MSOs than bad MSOs would indicate strong Link 16 interference. The unit could then make its own ADS-B message transmissions more reliable by preferentially choosing good MSOs, assuming the UAT unit it transmits to is subject to a similar degree of Link 16 interference. Since all UAT units in the network would be monitoring receptions and adjusting transmissions accordingly, the UAT affected by Link 16 interference would signal all those who could hear him to adjust themselves accordingly, and in that indirect way would improve his own reception performance even from transmitters who could not hear the Link 16 interference.

Presumably, optimum system performance (under the conditions that Link 16 interference is uniform in space and time) would be achieved by transmitting on good MSOs with the same probability as messages sent on them are being received. For the actual network, however, transmit preference toward good MSOs would need to be reduced (perhaps to  $\sim 0.75$  of the probability with which ADS-B messages sent on good MSOs are preferentially received) in order to allow UAT system response to stay localized to the times and locations where Link 16 interference is greatest.

The same general scheme could also be used when Link 16 transmissions are not synchronized to GPS. In this case, UAT MSOs would need to be divided into several equal sets, say 4, and they would be monitored without a priori knowledge of which set is most likely to be interfered with by Link 16 and which set is least likely. Again, once a discrepancy is identified in reception rates for the different MSO sets, transmissions could be made preferentially using MSOs for which receive probabilities are highest (as mentioned in Appendix slide 8).

It is also possible that an estimate of Link 16 interference severity could enable UAT performance to be optimized in other ways. For example, the number of ADS-B transmissions might be raised above once per second, or if erasure-based decoding were in use, the number of erasures permitted might be increased.

The improvement attainable would appear to be significant (up to perhaps twice the allowed Link 16 Burst Probability), but is difficult to quantify with any confidence without a full network simulation of both Link 16 and UAT networks. The cost of implementing such a scheme appears low, since the Link 16 monitoring could be done within the message handling software. It is not known to the author whether transmit MSO selection requires hardware modifications, but if so it seems likely they would be minor.

### 3.5 Combining Performance Results Against Link 16 With Previous Results

In the Link 16 interference simulations run by MITRE and by APL, the impact of interference from other UAT transmissions than the signal of interest was not modeled. In the MITRE working paper, it was suggested that the PCM for the combined (Link 16 plus other UAT) interference case could be estimated as the product of the PCM computed when only Link 16 interference is present, times the PCM computed in the previous ADS-B network simulations (when other UAT interference is present but Link 16 is absent).

The accuracy of this approach was explored by adding other UAT interference to the Link 16 interference simulation described earlier. As before, it was assumed that no bit errors occur when interference is off the air and that BER is 50% when interference is present. It was assumed that a UAT interferer may come on the air every MSO with equal and independent probability. PCMs were then computed as a function of Link 16 Burst Probability and of other UAT TX Probability. PCMs for the combined interference environment were compared with the products of the PCMs measured when either Link 16 or other UAT interference was present by itself. Both the UAT signal of interest and the other UAT interference signals were assumed to be the proposed Long ADS-B message, using a RS(64,34) block. (This investigation is described in the Appendix, slides 10-12)

For the situation investigated, the product PCM was found to overestimate the true PCM slightly (up to about 2% for PCMs in the range 75% to 90%). Although this error is not large, and most of it could be removed by an ad hoc fix to the PCM combining rule, larger PCM estimation errors can occur under different circumstances, for example for message designs using the strongest error-correcting codes.

Another problem is that these results are only valid for the assumed conditions of independence of Link 16 and UAT interference. This assumption is not warranted because there are nulls in the UAT receive antenna pattern so that as the receiving aircraft turns, Link 16 and UAT interference may rise and fall together, or one may rise as the other falls, depending on the directions of arrival of the dominant components. This dependence can cause larger errors for the simple product PCM.

Thus, while calculations using Link 16 interference by itself (as opposed to a full UAT plus Link 16 network simulation) can be used to rate the relative Link 16 tolerance of different mitigation approaches, such calculations should be used conservatively (i.e. allowing a margin for error) when estimating whether any given approach can achieve acceptable performance under combined conditions. Determining the appropriate size for the margin for error will require further study.

### 3.6 Impact of Denser Link 16 Operations

In the Link 16 interference simulations run by MITRE, the interference source was a single nearby (3 nm) transmitter, sending 258-hop messages, and operating at 100% TSDF. Although this is a severe environment, it may not represent the worst-case Link 16 interference environment that UAT should be designed to withstand. In particular, UAT is more sensitive to the *amount of time* Link 16 emissions are in the UAT band during the desired UAT message, than to the *strength* of those emissions (as long as they are at least as strong as the desired UAT message). As a result, environments with greater than 100% TSDF (due to stacked-net Link 16 operation) may impact UAT more severely than the single-transmitter MITRE environment even though the transmissions may be much weaker.

It is the author's understanding that current guideline allow DoD to operate Link 16 networks (without prior coordination outside DoD) such that all Link 16 transmitters within a 200 nm radius may sum to a combined TSDF of 100%, and that a ("proposed") set of restrictions is under consideration which would permit that radius to shrink to 100 nm and for transmitters at ranges between 100 and 200 nm to operate with an additional combined TSDF of 300%. These conditions may be more severe than the single-transmitter environment considered by MITRE.

In order to find out if the MITRE-proposed UAT coding/interleaving/bandwidth enhancements are adequate to combat realistic Link 16 interference, PCM vs. range calculations were carried out for these denser multi-transmitter Link 16 environments. The calculations were designed to be comparable to the MITRE PCM vs. range simulations for single-transmitter Link 16 interference.

As a first step, the calculations were validated by simulating the same single-transmitter case already investigated by MITRE, and verifying that comparable results were obtained (see Appendix, slides 13-17). Throughout this investigation, attention was confined to the long ADS-B message. PCM was computed for current, enhanced-coding and enhanced coding/bandwidth designs. Although PCM results were not exactly the same as those obtained by MITRE, they were close enough that the discrepancies could be due to simple statistical errors.

Next, the enhanced coding/bandwidth design was subjected to the "DoD-Proposed (?)" Link 16 environment. Several details of this environment were criticized at the Melbourne, FL meeting of the UAT MOPS Working Group, namely:

- Only the current Link 16 operational restrictions are definite. The looser "proposed" restrictions may not become operational.
- The longer 444-hop Link 16 messages were assumed to occupy up to 100% of the time slots for each network. It appears that only the shorter 258-hop messages can occur this often, and that the 444-hop messages can only occupy 258/444 or ~ 58% of the time slots of a given net.
- The closest-range transmitter was positioned only 1000 feet away, which was viewed as an unrealistically small separation.

In light of the above, the “DoD-Proposed (?)” Link 16 interference environment used to arrive at the results shown in Appendix slides 18 and 19 must be considered worse than realistic worst-case conditions. The corresponding performance results are included here as a point of reference. They show that under these severe conditions, substantial and probably unacceptable degradation would occur for the long ADS-B message, even if the enhanced-coding and enhanced-bandwidth design proposed by MITRE were used.

In order to achieve a better representation of a realistic worst-case Link 16 interference environment, an additional set of runs were made using 258-hop messages (instead of 444-hop) with the nearest transmitter being 3.2 nm away (instead of 1000 feet). The “DoD proposed” configuration was maintained., but an additional run was also made with the nearest stacked net transmitters beyond 200 nm (assumed current operational restrictions).

Two additional minor changes were made based on discussions at the Melbourne FL Working Group meeting:

- Every Link 16 hop was constrained to change the transmit frequency by at least 30 MHz.
- The UAT transmit frequency was set at 978 MHz. (For the earlier results, performance was the average of that at 981 and 993 MHz.)

As shown in Appendix slides 20-23, it was found that the “DoD-proposed” multiple transmitter Link16 environment was significantly worse (about twice as many message errors) than the single-transmitter environment assumed by MITRE. Performance under the “currently allowed” conditions, with stacked nets maintained at least 200 nm distant, appeared to differ only slightly from the MITRE-assumed environment.

The distances used by DoD for separating Link 16 transmitters are not necessarily equivalent to UAT-to-Link 16 separations. For example, consider three Link 16 networks, each consisting of two or more nearby platforms operating at a combined TSDF of 100%, and separated from one another by a little more than 200 nm. The participants in these three networks would be located near the corners of an equilateral triangle whose sides measure perhaps 210 nm. A UAT receiver near the center of the triangle would hear all three networks, at a combined TSDF of 300%, and all participants would be at ranges of only about  $210/\sqrt{3}$  or about 120 nm.

The above scenario, putting UAT between net participants instead of close to some of them, as done in slide 23, also meets a DoD separation of 200 nm. But it subjects the UAT to 300% TSDF within 150 nm, as opposed to only 100% for slide 23. A simulation was also run for this scenario and it was seen that its impact was much less severe than putting the UAT close to one of the networks (see slide 24).

Based on these results, it appears that worst-case operational Link16 environments will degrade the PCM achievable by UAT with the MITRE-proposed enhancements by 10% to 15% at ranges of about 100 nm. The lower number corresponds to Link 16

environments expected under current DoD constraints, while the larger number occurs under the assumed “DoD proposed” rules. Adding the effects of DME interferences and the slightly higher-than-product PCM combining discussed in Section 3.5, it appears that some additional UAT performance enhancements may be appropriate.

### **3.7 Frequency-Diversity (Dual-Channel) UAT Operation**

BAE Inc. have proposed a dual-channel variant of UAT designed to achieve increased interference resistance at the expense of increased spectrum occupancy. Their proposed waveform is modulated at a significantly higher rate (~5 Mchip/sec) than the current UAT and includes M-ary symbol encoding. To determine the impact of the frequency-diversity feature, separate from these other changes in the modulation waveform, a set of 2-channel simulations were run as part of the investigations of dense Link 16 environments reported in the preceding section (shown as “2-band” curves in Appendix slides 15-23).

Because Link 16 transmissions are spread out over many MHz, frequency diversity requires that the two UAT channels be well separated. For these simulations, a separation of 12 MHz was assumed. Diversity was assumed to permit achieving, on a bit-by-bit basis, the lowest BER occurring on either of the two channels in use. Each of the two channels was assumed to perform at the level of a single UAT channel, each with enhanced coding and enhanced bandwidth. Note that this approach also assumes that the total UAT TX power is doubled.

It was found that such a 2-channel design is capable of operating in even the worst Link 16 environments studied with little degradation. If total UAT TX power were split between the two channels, receiver noise would reduce performance somewhat at long ranges compared to these simulation results. Nevertheless, it can be seen that dual-channel frequency diversity operation can achieve most if not all of the required capability to operate in the presence of Link 16 interference.

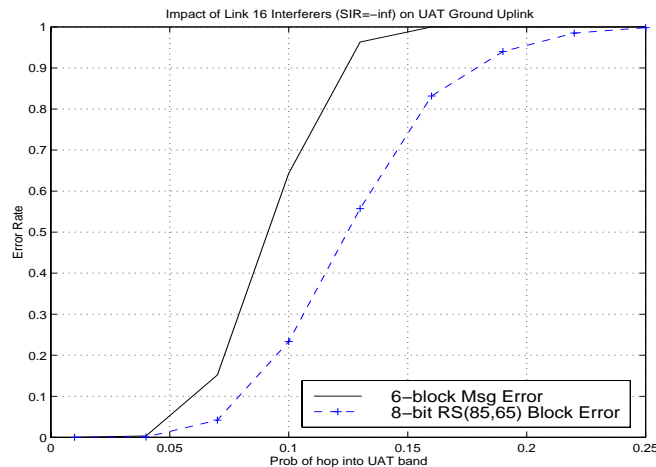
## Appendix: Slide Presentation of Simulation Approaches and Results

### *UAT Reception of Ground Uplink with Link16 Interference Approach*

- Matlab simulation
- Simplifying assumptions
  - $I \gg S \gg N$ 
    - When Link16 hops into the UAT band, BER = 50%
    - Otherwise, BER = 0%
  - Probability that Link16 occupies the UAT band for any given hop time is equal and independent of occupancy on other hop times
    - Performance comparisons of different receiver configurations can be reduced to comparisons of their curves of MER vs. probability of hop into band
    - Assumed hops occur every 13 UAT bits and Link16 dwell within hop is 6.5 bits
      - Neither hops nor Link16 dwells aligned with UAT bits
  - Initially included CRC verification, but dispensed with since results are essentially unchanged if correct message reception is defined as correct message RS decode on all blocks

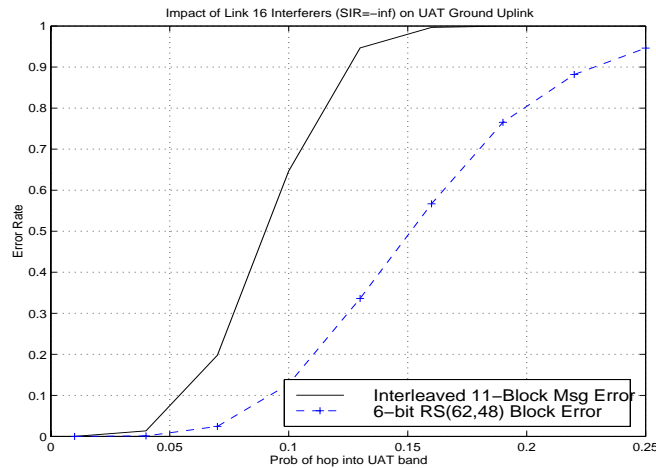
### Slide 1

### *UAT Reception of Ground Uplink with Link16 Interference 6 blocks of Interleaved 8-bit RS(85,65)*



### Slide 2

**UAT Reception of Ground Uplink with Link16 Interference**  
**11 blocks of 6-bit RS(62,48) + Interleaving**



**Slide 3**

**UAT Reception of Ground Uplink with Link16 Interference**  
**Simplified Approach (1 of 2)**

- Only use RS code blocks
  - Omit Synch & Pad parts of message
  - 4080-bits vice 4180 bits
  - Ignore CRC
- Assume Link16 interference bursts and hops are aligned with UAT bits
  - Assume burst lasts 7 bits, vice 6.5
- As before, assume
  - $I \gg S \gg N$
  - Probability that Link16 occupies the UAT band for any given hop time is equal and independent of occupancy on other hop times

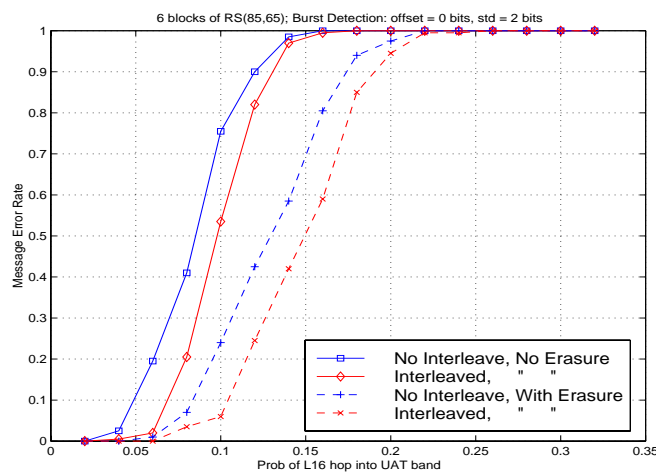
**Slide 4**

## ***UAT Reception of Ground Uplink with Link16 Interference Simplified Approach (2 of 2)***

- Assume Side Information to Detect L16 Interference Bursts
  - Use to erase affected bits
  - Expect imperfect erasure, i.e. error in determining when interference bursts start and stop
    - Assume Gaussian distribution, characterize by mean & standard deviation
    - Assume mean start time error = - mean stop time error, i.e. burst lengths may be systematically under or over-estimated
  - Assume side information might be derived from multiple-bit demodulation at 6\*chip rate
- Simulation didn't perform RS decode, instead, simply counted symbols in each block with wrong or erased bits, & assumed message is wrong iff:
  - No Erasure: For any RS block, {# of symbols with bit errors} > 10
  - Erasure: For any RS block, {# of symbols with erased bits + twice # of non-erased symbols with bit errors} > 20

### **Slide 5**

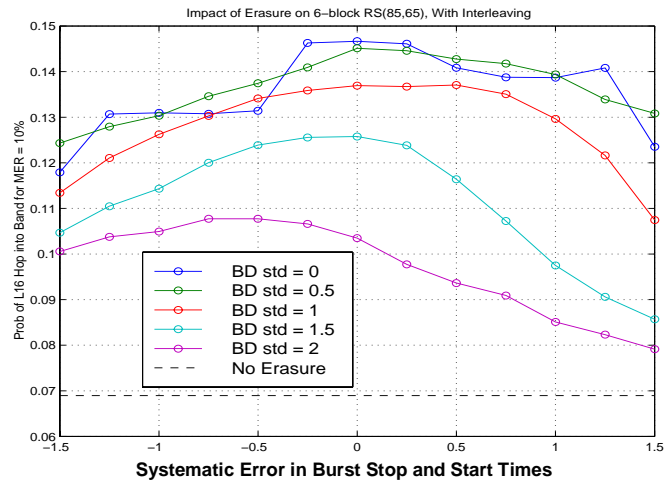
## ***UAT Reception of Ground Uplink with Link16 Interference 6 blocks of 8-bit RS(85,65)– Sample Impact of Erasure***



### **Slide 6**



## UAT Reception of Ground Uplink with Link16 Interference Interleaved 6 x RS(85,65)– Impact of Erasure



(e.g. +1 means detected start times average 1 bit late, and stop times average 1 bit early)

## Slide 7

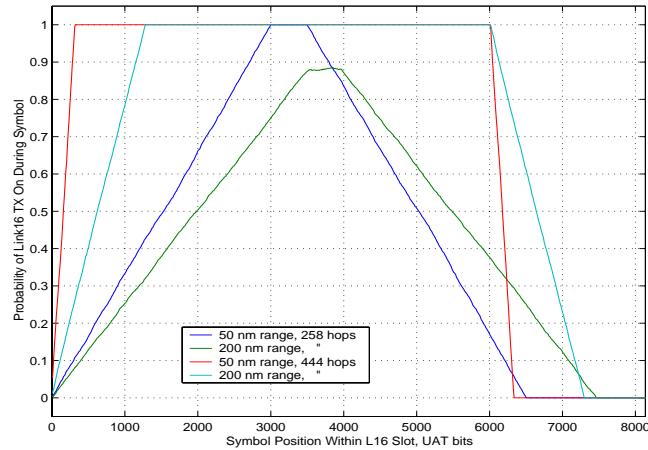
### Correlation of UAT Symbol Errors Caused by Link16 at Different Times Within Ground Uplink Message Fixed Link16/UAT Timing

- Synchronize UAT Ground Uplink to Link16 time slots
  - Current design has 32 slots. Each slot has:
    - Length = 5.5 msec + 12 msec guard band to air-to-air portion
    - 2 synch preambles (requires sample clock to coast for 1.96 msec)
    - 1.5 msec guard band to next slot
  - Synchronized design could have, e.g. 21 slots, each slot with:
    - Length = 8.5 msec + 9.5 msec guard band to air-to-air portion
    - 3 synch preambles (requires sample clock to coast for 2.46 msec)
    - 1 msec guard band to next slot
    - Longer transmission allows ~29% more throughput per slot, or more FEC
- Could also synchronize ADS-B transmissions, e.g.:
  - Divide ADS-B MSO's into 4 equal sets, by position in Link16 slot
  - UAT monitors # of ADS-B msg receipts for MSO's in each set
  - UAT preferentially transmits on MSO's in sets with most receipts
    - Transmit ratio mirrors reception ratio: TX ratio ~  $1 + .75 * (\text{receive ratio} - 1)$
    - 0.75 factor to stabilize dynamics and allow differences in time and location

## Slide 8

**Probability of Link16 TX Being On the Air  
During an Occupied L16 Slot  
(for Different L16 Msg Lengths and TX-RX Range Uncertainties)**

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**Slide 9**

**Accuracy of Computing PCM For Combined Link16 and UAT  
Interference As Product of PCMs For Each Separately  
Approach**

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- Timing assumptions
  - Link16:
    - TX on 1<sup>st</sup> 7 bits of each 13-bit hop
    - Prob. of TX in UAT band is independent from hop to hop
    - Hop boundary times randomized over 13-bit range relative to the start of the desired UAT message (integer # of bits)
  - UAT Interference:
    - TX may start on any MSO with probability independent from MSO to MSO
    - If TX starts on MSO, it continues for 412 bits (proposed enhanced Long ADS-B Message)
    - MSO times randomized over 260-bit range relative to the start of the desired UAT message (integer # of bits)
  - Desired UAT Message:
    - 368 bits, representing the RS(46,34) block of the proposed enhanced **Long ADS-B Message**

**Slide 10**

***Accuracy of Computing PCM For Combined Link16 and UAT  
Interference As Product of PCMs For Each Separately  
Approach (cont'd) and Result***

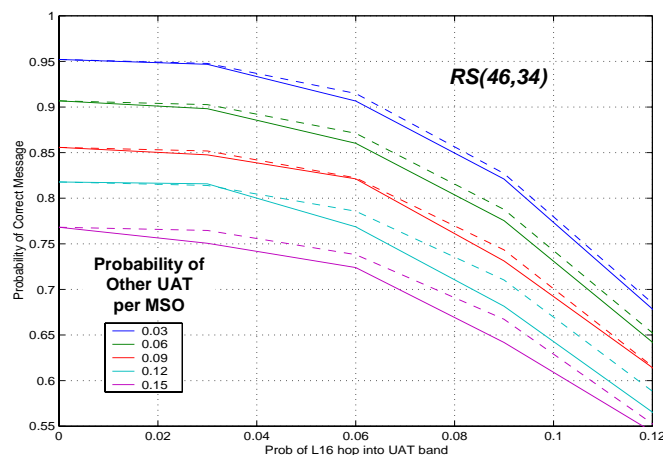
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- Compared PCM of each interferer separately with PCM of combined interference
  - 50% of bits were randomly set wrong if any interference was present, otherwise no bit errors
    - Equivalent to  $SNR = \text{inf}$ ,  $SIR = -\text{inf}$
  - Message was wrong if more than  $(n-k)/2 = 6$  symbols had errors
- Result:
  - $PCM(L16) * PCM(\text{Other UAT})$  overestimates  $PCM(L16 + \text{Other UAT})$  slightly (up to ~ 2%)

**Slide 11**

***PCM(L16+Other UAT) (solid lines)  
Vs. PCM(L16)\*PCM(Other UAT) (dashed lines)***

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**Slide 12**

### ***Impact on UAT of DoD-Proposed Link16 Limits Approach***

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- Attempted to reproduce MITRE (Wilson/Leiter) simulation results for Long ADS-B message
  - Used same assumptions for UAT and Link16 TX power, BER(S/N), Link16 TX spectrum, spherical spreading
  - RS decode not modeled; msg bad iff # of symbol errors >  $(n-k)/2$
- Checked against MITRE results
  - One 258-hop Link16 at 3 nm, 100% TSDF
- Then ran MITRE's Enhanced UAT against Proposed (?) DoD Link16 Limits
  - Used 444-hop messages, should have used 258-hop
  - One 50% TSDF at 1000'
  - Remaining 50% of that slot at 3 nm
  - 3 more stacked nets to give 300% TSDF at 100 nm
  - 3 more stacked nets to give 300% TSDF at 200 nm

### **Slide 13**

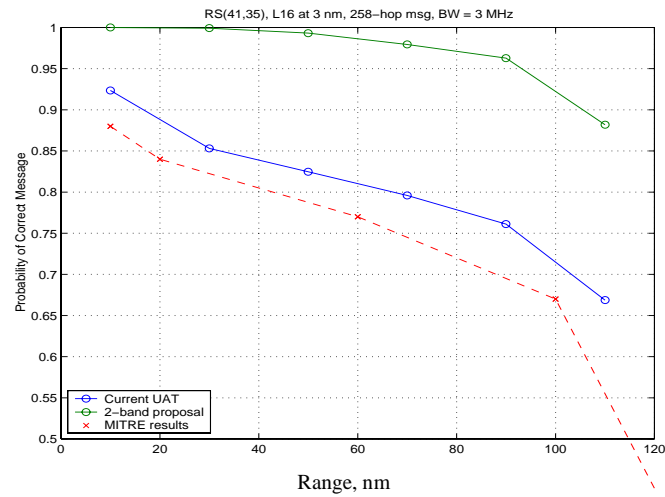
### ***Impact on UAT of DoD-Proposed Link16 Limits Results***

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- Wasn't able to reproduce MITRE results exactly
  - Results were in ballpark, but different
    - Simulation errors? Statistical errors?
- Couldn't be sure Link16 scenario was correct
  - 200 watt TX gave received levels of -29, -55, -85, -91 dBm for ranges of 1000', 3.2 nm, 100 nm, 200 nm
  - DoD quoted levels as -35, -65, -90, -100 dBm
  - So also re-ran at 50 watt TX: -35, -61, -91, -97 dBm
  - Also not sure interferer configuration is as intended
- With the above uncertainties, results indicate proposed enhancements may not be adequate for the proposed Link16 interference environment
- Also looked at performance of 2-channel frequency diversity, similar to BAE proposal (but no waveform change): Much better, apparently adequate

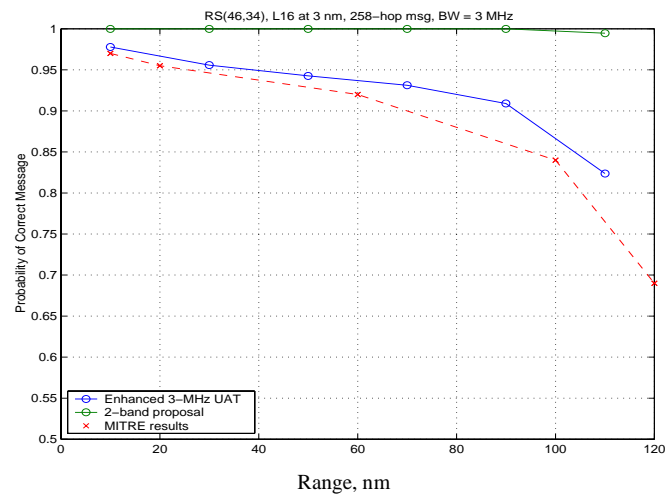
### **Slide 14**

## Comparison of Results For Current UAT



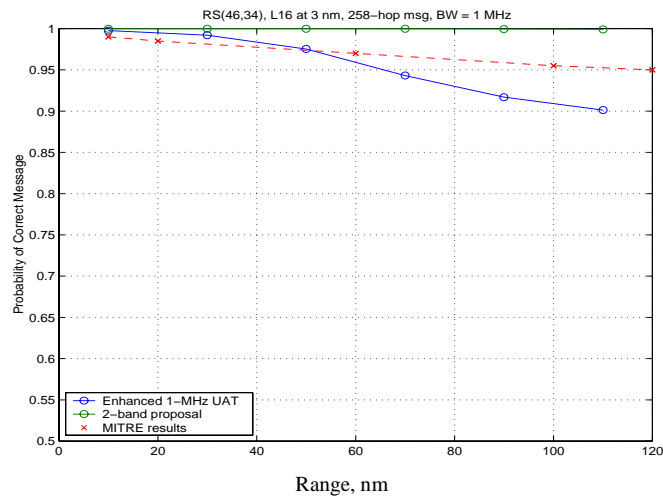
Slide 15

## Comparison of Results For Enhanced UAT (Bandwidth still = 3 MHz)



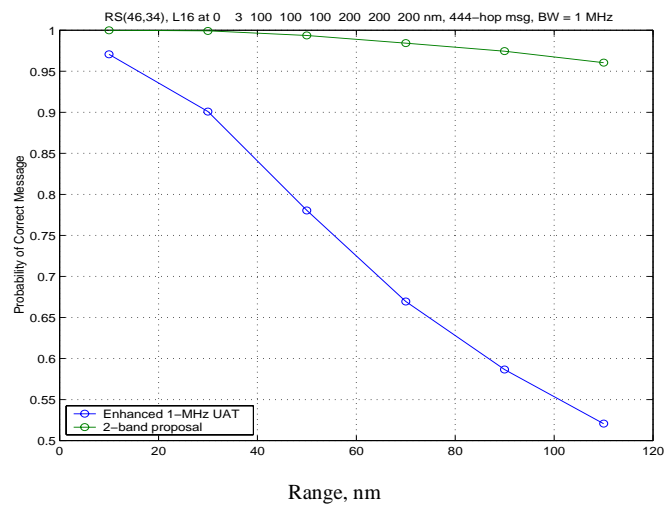
Slide 16

## Comparison of Results For Enhanced UAT (Bandwidth reduced to 1 MHz)



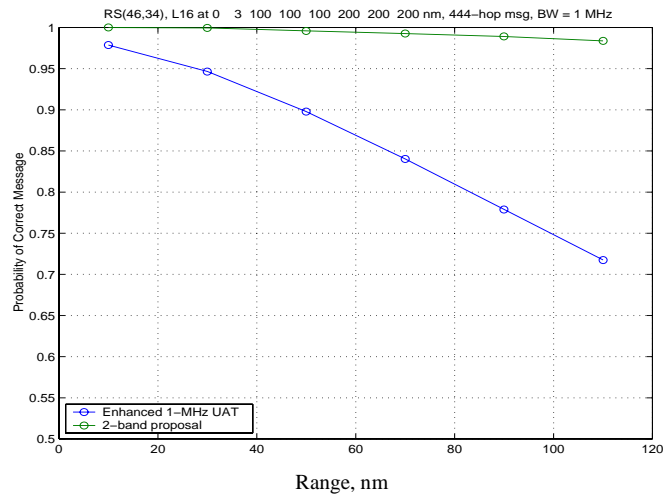
Slide 17

## DoD-Proposed (?) Link16 Environment Against Enhanced 1-MHz Bandwidth UAT



Slide 18

## **DoD-Proposed (?) Link16 Environment** **Link16 TX Power Reduced to 50 Watt**



### **Slide 19**

## **Impact on UAT of Dense Link16 Environments** **Modified Approach**

- Based on discussion at Melbourne WG meeting, made following changes:
  - Reduced Link16 from 444-hop to 258-hop messages to conform with definition of TSDF
  - Nearby Link16 transmitters moved out from 1000' / 3.2 nm to 3.2 / 10 nm
  - Link16 transmitters at 100 nm and 200 nm spread slightly in range
    - So their transmissions don't coincide in time
  - Also investigated case with no Link16 transmitters at 100 nm
    - Consistent with Current Uncoordinated Operational Restrictions?
  - (Returned to 200 W Link16 TX power)

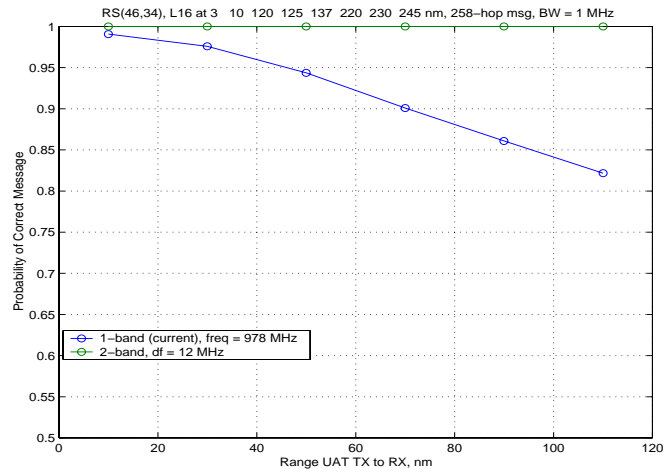
### **Slide 20**

## ***Impact on UAT of Dense Link16 Environment Results***

- Results:
  - Multiple Link16 transmitters at just beyond 100 nm add significant degradation to UAT ADS-B message copy
  - Observed ~ twice as many message errors under the “DoD Proposed (?)” scenario compared to the MITRE scenario (100% TSDF at 3 nm)
    - For MITRE-proposed enhanced long ADS-B message
    - PCM ~ 90% at 70 nm
  - Multiple 200-watt Link16 transmitters beyond 200 nm have small impact
  - MITRE-proposed enhancements may not be adequate for the combined [ Other UAT + DME + “Proposed” Link16 ] interference environment
  - No errors seen for 2-channel frequency diversity approach

### **Slide 21**

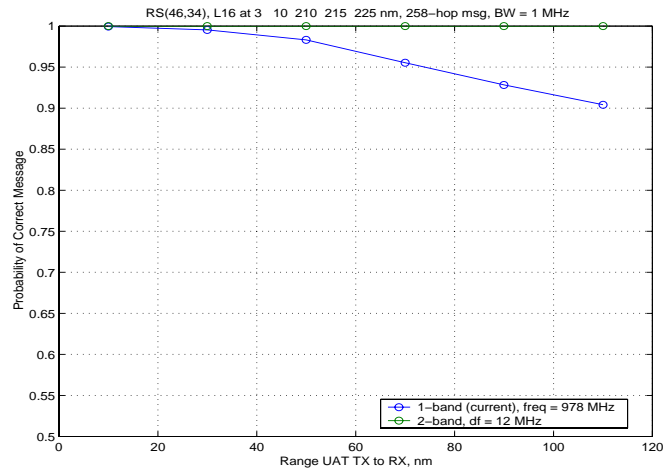
## ***DoD-Proposed (?) Environment (Distant Link16 TX at ~100 & ~200 nm) Against Enhanced 1-MHz Bandwidth UAT***



### **Slide 22**

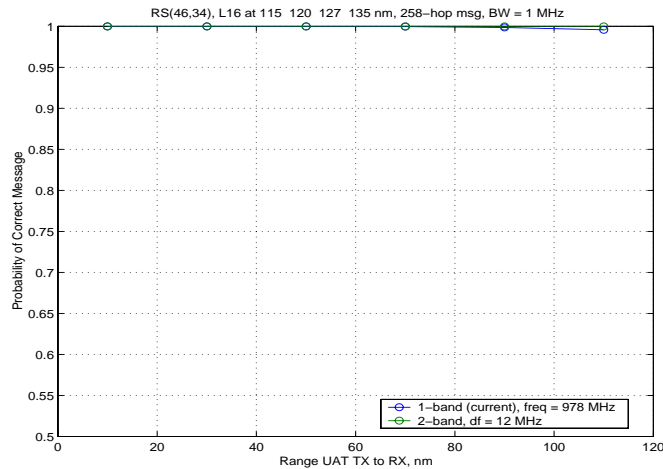


**Current DoD Allowed (?) Environment  
(Distant Link16 TX only at ~200 nm)  
Against Enhanced 1-MHz Bandwidth UAT**



**Slide 23**

**Current DoD Allowed (?) Environment  
(Centered among 3 100%-TSDF Link16 nets ~200 nm apart)  
Against Enhanced 1-MHz Bandwidth UAT**



**Slide 24**